

**INFLUENCE OF BEHAVIOUR FACTOR ON
SEISMIC DESIGN AND PERFORMANCE OF
REINFORCED CONCRETE MOMENT
RESISTING FRAME IN MALAYSIA**

MOHD IRWAN BIN ADIYANTO

UNIVERSITI SAINS MALAYSIA

2016

**INFLUENCE OF BEHAVIOUR FACTOR ON
SEISMIC DESIGN AND PERFORMANCE OF REINFORCED
CONCRETE MOMENT RESISTING FRAME IN MALAYSIA**

by

MOHD IRWAN BIN ADIYANTO

**Thesis submitted in fulfillment of the requirements
for the Degree of
Doctor of Philosophy**

March 2016

ACKNOWLEDGEMENT

By the name of Allah, Most Gracious, Most Merciful

On the completion of this thesis, I would like to present my highest gratitude to Allah S.W.T., for His love and mercy. Praise and peace be upon Prophet Muhammad S.A.W, his family, and his companions.

Firstly, I like to express my high appreciation to my supervisor Assoc. Prof. Dr. Taksiah A. Majid and to my co-supervisor, Dr. Fadzli Mohamed Nazri for their great commitment in guiding, facilitating, motivate and support during my hard moment in completing this research work. Special thanks for Assoc. Prof. Dr. Norhayati Abdul Hamid for her guidance and advice in order to conduct the cyclic loading test. I also like to appreciate all students and technicians at Heavy Structure Laboratory, Faculty of Civil Engineering, Universiti Teknologi Mara for their commitment during the construction and test. This is also the best moment to acknowledge and extend my gratitude to the financial support by Research University grant sponsored by Universiti Sains Malaysia and to the Mybrain15 program from Ministry of Higher Education Malaysia. A high appreciation also addressed to School of Civil Engineering, Universiti Sains Malaysia for all accommodations prepared for this research work.

To my father Adiyanto Ali, my siblings Zalina and Ali Imran, your support will remain deep in my heart. To my late mother Hamidah Mohd Noh, this achievement is a special dedication for you.

TABLE OF CONTENTS

	PAGE
ACKNOWLEDGEMENT	ii
TABLE OF CONTENTS	iii
LIST OF TABLES	viii
LIST OF FIGURES	x
LIST OF ABBREVIATIONS	xvi
LIST OF SYMBOLS	xvii
ABSTRAK	xx
ABSTRACT	xxii
 CHAPTER 1 - INTRODUCTION	
1.1 Background	1
1.2 Damage observation on RC buildings due to 2015 Ranau earthquake	5
1.3 Problem statement	13
1.4 Objectives	17
1.5 Scope of works	18
1.6 Thesis outline	19
 CHAPTER 2 - LITERATURE REVIEW	
2.1 Introduction	22
2.2 Basic concept of behaviour factor, q	22
2.3 Influence of behaviour factor, q on structural performance	24

2.4	Cyclic loading test on RC frame	30
2.5	Effect of repeated earthquake on structural performance	36
2.6	Summary	41

CHAPTER 3 - RESEARCH METHODOLOGY

3.1	Introduction	44
3.2	2 dimension RC moment resisting frame models	47
3.2.1	Fundamental period of vibrations, T_1	49
3.3	Derivation of earthquake load	51
3.3.1	Base shear force, F_b	51
3.3.2	Design response spectrum	52
3.3.2.1	Design ground acceleration, a_g	54
3.3.2.2	Behaviour factor, q	57
3.3.3	Mass of structure, m	62
3.3.4	Distribution of lateral load	65
3.4	Seismic design to Eurocode 8	65
3.4.1	Seismic design of beam	66
3.4.2	Seismic design of column	75
3.5	Cyclic loading test	82
3.5.1	Design of N2-DB model	82
3.5.2	Construction phases of N2-DB model	85
3.5.3	Experimental setup	94
3.5.4	Testing procedure, loading regime, and expected outcome	98
3.5.5	Analysis of experimental hysteresis loop	102

3.5.6	Development of numerical hysteresis loop using Hysteres Program	104
3.6	Nonlinear Time History Analysis	107
3.6.1	Section analysis using CUMBIA	108
3.6.2	Ruaumoko 2D Program	108
3.6.3	Preparation of single ground motion records	111
3.6.4	Preparation of repeated ground motion records	114
3.6.5	Structural evaluation based on performance level	117
3.7	Summary	118
CHAPTER 4 - RESULTS AND DISCUSSION		
4.1	Introduction	121
4.2	Base shear force, F_b and distribution of lateral load	122
4.3	Influence of behaviour factor, q on seismic design	123
4.3.1	Influence of behaviour factor, q on design of beam flexural reinforcement	124
4.3.2	Influence of behaviour factor, q on design of beam shear reinforcement	129
4.3.3	Influence of behaviour factor, q on design of column flexural reinforcement	133
4.3.4	Influence of behaviour factor, q on design of column confinement reinforcement	138
4.3.5	Influence of behaviour factor, q on design of confinement reinforcement in beam-column joints	145

4.3.6	Influence of behaviour factor, q on total weight of steel reinforcement	147
4.4	Cyclic loading test	152
4.4.1	Concrete compression test	153
4.4.2	Visual damage observation during the experimental work	155
4.4.3	Hysteresis loop developed from experimental result	171
4.4.4	Estimation of yield and ultimate displacement	176
4.4.5	Global stiffness	180
4.4.6	Global ductility	184
4.4.7	Input data to develop the numerical hysteresis loop	185
4.4.8	Comparison between the experimental and numerical hysteresis loops	186
4.5	Evaluation on structural performance	188
4.5.1	Influence of behaviour factor, q on distribution of IDR_{mean}	188
4.5.2	Influence of near field and far field earthquakes on IDR_{mean}	193
4.5.3	Influence of soil type on IDR_{mean}	196
4.5.4	Influence of repeated earthquake on IDR_{mean}	199
4.6	Estimation of maximum IDR_{mean}	208

CHAPTER 5: CONCLUSIONS

5.1	Conclusions	213
5.1.1	Influence of behaviour factor, q on seismic design	213
5.1.2	Cyclic loading test on N2-DB model	215
5.1.3	Influence of single and repeated earthquake on structural performance	216

5.2	Recommendations for future research works	218
	REFERENCES	220
APPENDIX A	2 DIMENSION RC FRAME	
APPENDIX B	MASS OF STRUCTURE AND BASE SHEAR FORCE	
APPENDIX C	EXAMPLE OF SEISMIC DESIGN	
APPENDIX D	DESIGN DETAIL OF N2-DB MODEL	
APPENDIX E	EXAMPLE OF RUAUMOKO 2D INPUT DATA	
APPENDIX F	GROUND MOTION RECORDS	
APPENDIX G	DESIGN DETAIL OF ALL FRAMES	
APPENDIX H	TAKING OFF DETAIL OF ALL FRAMES	
APPENDIX I	EXPERIMENTAL HYSTERESIS LOOPS	
APPENDIX J	NONLINEAR TIME HISTORY ANALYSES	
	LIST OF PUBLICATIONS	

LIST OF TABLES	Page
Table 1.1 : Damage type and structural performance levels for RC building	5
Table 3.1 : Weight of materials	48
Table 3.2 : Estimated fundamental period of vibration, T_1	50
Table 3.3 : Method of analysis based on regularity of structure	51
Table 3.4 : Main parameters to develop Type 1 design response spectrum	53
Table 3.5 : Importance classes and importance factors for buildings	55
Table 3.6 : Basic value of the behaviour factor, q_0 for systems regular in elevation	59
Table 3.7 : Proposed value of behaviour factor, q for multi-storey and multi-bay RC frame	60
Table 3.8 : Example of label used for designed frames	62
Table 3.9 : Specific target drift and lateral displacement	99
Table 3.10 : Example of selected NFE ground motion records for Soil Type B	113
Table 3.11 : Example of selected FFE ground motion records for Soil Type B	113
Table 3.12 : Example of selected NFE ground motion records for Soil Type D	113
Table 3.13 : Example of selected FFE ground motion records for Soil Type D	114
Table 3.14 : Multiplication factor to generate repeated earthquake	115
Table 4.1 : Flexural design parameter of B1 for N3D frames near interior support	126

Table 4.2 : Design parameter of shear reinforcement of B1 for N3D frames	131
Table 4.3 : Design parameter of flexural reinforcement of CA-interior (N3D frames)	135
Table 4.4 : Design parameter of flexural reinforcement of CA-exterior (N3D frames)	137
Table 4.5 : Design parameter of confinement reinforcement of CA-interior (N3D frames)	141
Table 4.6 : Design parameter of confinement reinforcement of CA-exterior (N3D frames)	144
Table 4.7 : Maximum displacement and lateral load of LVDT 1 (1 st Cycle)	173
Table 4.8 : Maximum displacement and lateral load of LVDT 1 (2 nd Cycle)	173
Table 4.9 : Maximum displacement and lateral load of LVDT 2 (1 st Cycle)	175
Table 4.10 : Maximum displacement and lateral load of LVDT 2 (2 nd Cycle)	175
Table 4.11 : Elastic Stiffness, $K_{elastic}$ and effective stiffness, K_e for N2-DB model	183
Table 4.12 : Global ductility of N2-DB model	184
Table 4.13 : Input details for Hysteres program	185
Table 4.14 : Percentage of difference on structural behaviour between experimental and numerical hysteresis loops	187
Table 4.15 : Coefficient for estimation of maximum IDR_{mean} on Soil Type B ($a_{gR} = 0.12g$)	211
Table 4.16 : Coefficient for estimation of maximum IDR_{mean} on Soil Type D ($a_{gR} = 0.12g$)	212

LIST OF FIGURES	Page
Figure 1.1 : Earthquake events since 1972 to a depth of 50 km	2
Figure 1.2 : Location of 2015 Ranau earthquake	2
Figure 1.3 : Damages on RC beams due to 2015 Ranau earthquake	8
Figure 1.4 : Minor damages on RC columns due to 2015 Ranau earthquake	9
Figure 1.5 : Significant damages on RC columns due to 2015 Ranau earthquake	10
Figure 1.6 : Total damage on RC columns due to 2015 Ranau earthquake	11
Figure 1.7 : Damage on RC beam-column joints due to 2015 Ranau earthquake	12
Figure 1.8 : Failure mechanisms of RC buildings due to 2015 Ranau earthquake	13
Figure 2.1 : Comparison between elastic and inelastic design force	16
Figure 2.2 : 2 storey double bay RC frame in previous experimental work	31
Figure 2.3 : Hysteresis loop from cyclic loading test	33
Figure 2.4 : Backbone curve enveloping the hysteresis loop	34
Figure 2.5 : Comparison between numerical and experimental hysteresis loops of RC column	35
Figure 2.6 : Comparison between numerical and experimental hysteresis loops of bare frame RC model	35
Figure 3.1 : Flow chart of research methodology	46
Figure 3.2 : Elevation view of three storey RC frame	48
Figure 3.3 : Seismic hazard map for Peninsular Malaysia	56
Figure 3.4 : Seismic hazard map for Eastern Malaysia	56

Figure 3.5 : Design response spectrum for Soil Type B	61
Figure 3.6 : Design response spectrum for Soil Type D	61
Figure 3.7 : Standard label arrangement for all frames	62
Figure 3.8 : Elevation view of floor mass	64
Figure 3.9 : Tributary area for calculation of floor mass	64
Figure 3.10 : Distribution of lateral load on three storey RC frame	65
Figure 3.11 : Beam sections considered for design	67
Figure 3.12 : Flow chart of beam design to Eurocode 8	71
Figure 3.13 : Basic detailing for beam with DCM	74
Figure 3.14 : Derivation of moment resistance of column, M_{Rc}	76
Figure 3.15 : Flow chart of column design to Eurocode 8	78
Figure 3.16 : Confinement of concrete core in square column	80
Figure 3.17 : Basic detailing for column with DCM	81
Figure 3.18 : 3 dimension and elevation view of N2-DB model	83
Figure 3.19 : Size of section and steel reinforcement details	84
Figure 3.20 : Construction phases of N2-DB model	85
Figure 3.21 : Construction phase of foundation	86
Figure 3.22 : Construction phase of first level columns	88
Figure 3.23 : Construction phase of first level beams	90
Figure 3.24 : Construction phase of second level columns	91
Figure 3.25 : Construction phase of second level beams and rigid slab	93
Figure 3.26 : Final phase of construction	94
Figure 3.27 : Schematic view of location of LVDTs	96
Figure 3.28 : Pre-test setup of N2-DB model	97
Figure 3.29 : Loading regime for cyclic loading test	99

Figure 3.30 : Procedure of cyclic loading test on N2-DB model	100
Figure 3.31 : Basic estimation of yield displacement, Δ_y	102
Figure 3.32 : Illustration of initial stiffness and secant stiffness concepts related to a structure's full nonlinear response	103
Figure 3.33 : Sequence of input in Hysteres program	105
Figure 3.34 : Degrading strength rule	106
Figure 3.35 : Modified Takeda Degrading Stiffness hysteresis rule	107
Figure 3.36 : Sequence of input in Ruaumoko 2D program	110
Figure 3.37 : Propagation of energy wave in NFE	112
Figure 3.38 : Standard profile of ground motion records	116
Figure 3.39 : Definition of interstorey drift ratio	117
Figure 4.1 : Influence of behaviour factor, q on the base shear force, F_b	123
Figure 4.2 : Comparison of steel for beam flexural reinforcement of B1 on Soil Type D	125
Figure 4.3 : Comparison of steel for beam flexural reinforcement of B1 on Soil Type B	128
Figure 4.4 : Comparison of steel for beam shear reinforcement of B1 on Soil Type D	130
Figure 4.5 : Comparison of steel for beam shear reinforcement of B1 on Soil Type B	132
Figure 4.6 : Comparison of steel for column flexural reinforcement of CA-interior on Soil Type D	134
Figure 4.7 : Comparison of steel for column flexural reinforcement of CA-exterior on Soil Type D	136

Figure 4.8 : Comparison of steel for column confinement reinforcement of CA-interior on Soil Type D	139
Figure 4.9 : Comparison of steel for column confinement reinforcement of CA-exterior on Soil Type D	143
Figure 4.10 : Comparison of confinement reinforcement in beam-column joint of CA-interior on Soil Type D	146
Figure 4.11 : Comparison of confinement reinforcement in beam-column joint of CA-exterior on Soil Type D	147
Figure 4.12 : Total weight of steel for N3D frames	149
Figure 4.13 : Total weight of steel for N6D frames	149
Figure 4.14 : Total weight of steel for N9D frames	150
Figure 4.15 : Total weight of steel for N12D frames	150
Figure 4.16 : Total weight of steel for N3B frames	151
Figure 4.17 : Total weight of steel for N6B frames	151
Figure 4.18 : Total weight of steel for N9B frames	151
Figure 4.19 : Total weight of steel for N12B frames	152
Figure 4.20 : Compressive cylinder strength, f_{ck} for N2-DB model	154
Figure 4.21 : Compressive cube strength, $f_{ck, cube}$ for N2-DB model	154
Figure 4.22 : Hairline cracks at 0.75% and 1.00% target drifts	156
Figure 4.23 : Cracks elongation at 1.25% and 1.50% target drifts	157
Figure 4.24 : Damage observation at 1.75% and 2.00% target drifts	159
Figure 4.25 : Damage observation at 2.25% and 2.50% target drifts	160
Figure 4.26 : Damage observation at 2.75% and 3.00% target drifts	162
Figure 4.27 : Plan view of first level with alphabetical joint labels	163
Figure 4.28 : Post-test assessment on beam-column joints	164

Figure 4.29 : Post-test assessment on spalling of concrete cover	165
Figure 4.30 : Post-test assessment on the flexural cracks at first level beam	167
Figure 4.31 : Predicted bending moment diagram from SAP 2000 computer analysis	169
Figure 4.32 : Flexural cracks pattern on beams from previous study	170
Figure 4.33 : Experimental hysteresis loop for LVDT 1	172
Figure 4.34 : Experimental hysteresis loop for LVDT 2	174
Figure 4.35 : Estimation of Δ_y and Δ_u for N2-DB model (LVDT 1)	178
Figure 4.36 : Estimation of Δ_y and Δ_u for N2-DB model (LVDT 2)	179
Figure 4.37 : Estimation of $K_{elastic}$ and K_e for N2-DB model (LVDT 1)	181
Figure 4.38 : Estimation of $K_{elastic}$ and K_e for N2-DB model (LVDT 2)	182
Figure 4.39 : Comparison between experimental and numerical hysteresis loops	186
Figure 4.40 : Influence of behaviour factor, q on distribution of IDR_{mean} of frames on Soil Type D	191
Figure 4.41 : Maximum storey drift for 3 storey model with various value of behaviour factor, q	192
Figure 4.42 : Maximum storey drift for 18 storey model with various value of behaviour factor, q	192
Figure 4.43 : Influence of behaviour factor, q on distribution of IDR_{mean} of frames on Soil Type B	193
Figure 4.44 : Comparison of IDR_{mean} on Soil Type D due to NFE and FFE	195
Figure 4.45 : Comparison of IDR_{mean} on Soil Type B due to NFE and FFE	196
Figure 4.46 : Comparison of IDR_{mean} on Soil Type B and Soil Type D due to NFE	197

Figure 4.47 : Comparison of IDR_{mean} on Soil Type B and Soil Type D due to FFE	198
Figure 4.48 : Comparison of IDR_{mean} on Soil Type D due to Case 1 and Case 2 of NFE	200
Figure 4.49 : Maximum interstorey drift ratio due to single and repeated earthquake	201
Figure 4.50 : Comparison of IDR_{mean} on Soil Type D due to Case 1 and Case 2 of FFE	202
Figure 4.51 : Maximum IDR_{mean} of Case 1 and Case 2 due to FFE on Soil Type B	204
Figure 4.52 : Maximum IDR_{mean} of Case 1 and Case 2 due to NFE on Soil Type B	205
Figure 4.53 : Maximum IDR_{mean} of Case 1 and Case 2 due to FFE on Soil Type D	206
Figure 4.54 : Maximum IDR_{mean} of Case 1 and Case 2 due to NFE on Soil Type D	207
Figure 4.55 : Estimation of maximum IDR_{mean} on Soil Type D due to repeated NFE	210

LIST OF ABBREVIATIONS

CP	Collapse prevention
DCH	Ductility class high
DCL	Ductility class low
DCM	Ductility class medium
FFE	Far field earthquake
IDR	Interstorey drift ratio
IDR _{mean}	Mean interstorey drift ratio
IO	Immediate occupancy
K _e	Secant or effective stiffness
K _{elastic}	Elastic stiffness
LS	Life safety
LVDT	Linear variables displacement transducer
MDOF	Multi degree of freedom
MMD	Malaysia meteorological department
NFE	Near field earthquake
NTHA	Nonlinear time history analysis
PEER	Pacific Earthquake Research Center
PGA	Peak ground acceleration
RC	Reinforced concrete
SDOF	Single degree of freedom

LIST OF SYMBOLS

Δ_u	Ultimate displacement
Δ_y	Yield displacement
μ_φ	Curvature ductility factor
a_g	Design ground acceleration on type A ground
a_{gR}	Reference peak ground acceleration
$A_{s_{prov}}$	Total area of steel provided
$A_{s_{req}}$	Total area of steel required
A_{sw}/s_{prov}	Total area of steel provided for shear and its spacing of bar
A_{sw}/s_{req}	Total area of steel required for shear and its spacing of bar
A_{swx}	Total area of confinement reinforcement provided along x direction
A_{swy}	Total area of confinement reinforcement provided along y direction
b_0	Width of column confined core
b_c	Column gross cross-sectional width
b_i	Distance between consecutive engaged bars
d_{bL}	Diameter of longitudinal bar
d_{bw}	Diameter of shear or confinement bar
E	Earthquake load
F_b	Base shear force
f_{cd}	Design value of concrete compressive strength
f_{ck}	Characteristic cylinder strength of concrete
f_{ctm}	Mean value of tensile strength of concrete
F_i	Lateral load on storey i
F_u	Ultimate load

f_y	Yield strength of reinforcement
f_{yd}	Design value of yield strength of steel
f_{ywd}	Design yield strength of the shear reinforcement
g	Acceleration due to gravity, m/s^2
G_k	Dead load
H	Storey height
h_0	Depth of column confined core
h_c	Width of the column
h_w	Depth of beam
k_D	Factor reflecting the ductility class
M	Bending moment
m	mass of structure
M_{Rb}	Design moment resistance of beam
M_{Rc}	Design moment resistance of column
M_w	Magnitude of earthquake intensity
N	Number of storey
P	Axial load of column
q	Behaviour factor
Q_k	Live load
R	Strength reduction factor
S	Soil factor
s	Spacing of bar
$S_d(T_1)$	Ordinate of the design spectrum at period T_1
s_{max}	Maximum spacing of bar
T_1	Fundamental period of vibration

T_B	Lower limit of the period of the constant spectral acceleration branch
T_C	Upper limit of the period of the constant spectral acceleration branch
T_D	Beginning of the constant displacement response range of the spectrum
V	Shear force
ν_d	Normalised design axial force in column
γ_I	Importance factor
γ_{Rd}	Model uncertainty factor on the design value of resistance
$\epsilon_{sy,d}$	Design value of tension steel strain at yield
λ	Correction factor
μ	Ductility
ρ	Reinforcement ratio in the tension zone
ρ'	Reinforcement ratio in the compression zone
ρ_{max}	Maximum reinforcement ratio
ρ_{min}	Minimum reinforcement ratio
$\Psi_{E,i}$	Combination coefficient for variable action
$\omega_{wd\ prov}$	Mechanical volumetric ratio of confining hoops provided
$\omega_{wd\ req}$	Mechanical volumetric ratio of confining hoops required

**PENGARUH FAKTOR KELAKUAN KE ATAS
REKABENTUK SEISMIC DAN PRESTASI KERANGKA MOMEN KONKRIT
BERTETULANG DI MALAYSIA**

ABSTRAK

Gempa bumi sederhana yang terjadi pada 5 Jun 2015 di Ranau, Sabah, dengan magnitude 5.9 telah menyebabkan kerosakan pada bangunan-bangunan. Dengan itu, adalah penting untuk mempertimbangkan rekabentuk seismic untuk bangunan-bangunan baru di wilayah tersebut. Dalam rekabentuk seismic, suatu konsep yang dinamakan sebagai faktor kelakuan yang berkait rapat dengan kemuluran telah dicadangkan. Baru-baru ini terdapat komen dan cadangan bahawa nilai faktor kelakuan sekarang patut diganti. Dengan itu, adalah penting untuk mengkaji kesan perubahan nilai faktor kelakuan dari dua perspektif iaitu reka bentuk dan prestasi. Selain itu, aturan histeresis mewakili kelakuan struktur apabila dikenakan beban kitaran sisi seperti gempa bumi. Kesesuaian sesuatu aturan histeresis untuk digunakan dalam program komputer bagi analisis sejarah masa tidak linear perlu diperiksa. Di wilayah seismic tinggi, kejadian gempa bumi berulang tidak boleh diabaikan dalam analisis struktur kerana ia mencetuskan kerosakan yang lebih besar ke atas sistem struktur. Dengan itu, pengaruh gempa bumi berulang di wilayah seismic medium di Malaysia juga perlu disiasat. Tesis ini membentangkan pengaruh faktor kelakuan ke atas rekabentuk seismic bagi bangunan kerangka penahan momen konkrit bertetulang di Malaysia. Rekabentuk seismic telah dijalankan untuk kemuluran kelas pertengahan dengan faktor kelakuan dari 2.3 hingga 5.5 merujuk kepada Eurocode 8. Ujian beban kitaran sisi juga telah dijalankan untuk mengkaji kelakuan struktur apabila dikenakan

beban sisi. Ia juga penting untuk memeriksa kesesuaian *Modified Takeda Degrading Stiffness* sebagai aturan histeresis bagi analisis sejarah masa tidak linear. Akhir sekali, prestasi struktur bagi semua kerangka yang telah direkabentuk dinilai dengan analisis sejarah masa tidak linear dengan mempertimbangkan gempa-gempa tunggal dan berulang. Kajian ini menyumbang kepada penilaian terhadap nilai faktor kelakuan berdasarkan rekabentuk dan prestasi struktur. Selain itu, kajian ini juga memeriksa kesesuaian *Modified Takeda Degrading Stiffness* sebagai aturan histeresis. Sebagai kesimpulan, nilai faktor kelakuan sangat mempengaruhi rekabentuk seismik. Jumlah berat besi pengukuhan boleh dikurangkan sehingga 36.2% dengan menggunakan faktor kelakuan tinggi dalam rekabentuk. Daripada ujian beban kitaran sisi, boleh disimpulkan bahawa *Modified Takeda Degrading Stiffness* sesuai untuk digunakan sebagai aturan histeresis dalam analisis sejarah masa tidak linear. Nilai kekakuan nyahbeban, α adalah bersamaan 0.1 sementara nilai kekakuan pembebanan semula, β adalah bersamaan 0.4. Berdasarkan penilaian ke atas prestasi struktur, magnitud maksimum bagi anjakan antara tingkat disebabkan oleh gempa bumi berulang mencapai sehingga 30.1% hingga 40.6% lebih tinggi daripada gempa bumi tunggal. Dengan itu, faktor kelakuan dari 2.3 hingga 5.5 adalah diterima untuk digunakan bagi rekabentuk seismik bangunan kerangka penahan momen konkrit bertetulang baru di atas tanah jenis B di wilayah seismik pertengahan di Malaysia. Di atas tanah jenis D, faktor kelakuan dihadkan dari 2.3 hingga 4.54.

**INFLUENCE OF BEHAVIOUR FACTOR ON
SEISMIC DESIGN AND PERFORMANCE OF REINFORCED
CONCRETE MOMENT RESISTING FRAME IN MALAYSIA**

ABSTRACT

A moderate earthquake which occurred on 5th June 2015 in Ranau, Sabah, with M_w 5.9 had caused damages on buildings. Therefore, it is important to consider seismic design for new buildings in that region. In seismic design, a concept namely as behaviour factor, q which strongly relates with ductility was proposed. Recently, there are comments and suggestion that the current value of behaviour factor, q shall be replaced. Therefore, it is importance to study the effect of changing the value of behaviour factor, q from two different perspectives which is design and performance. Besides, hysteresis rule represents the structural behaviour when subjected to cyclic lateral load like earthquake. The suitability of a hysteresis rule to be used in computer program for nonlinear time history analysis has to be checked. In high seismic region, the occurrence of repeated earthquake cannot be neglected in structural analysis since it induces greater damage on structural system. Therefore, the influence of repeated earthquake in medium seismic region in Malaysia also has to be investigated. This thesis presents the influence of behaviour factor, q on seismic design for reinforced concrete moment resisting frame buildings in Malaysia. The seismic design had been conducted for ductility class medium with behaviour factor, q from 2.3 to 5.5 by referring to Eurocode 8. The cyclic loading test also had been conducted to investigate the structural behaviour when subjected to lateral load. It is also important to check to suitability of Modified Takeda Degrading Stiffness as hysteresis rule for nonlinear

time history analysis. Finally, the structural performance of all designed frames had been evaluated by using nonlinear time history analysis considering single and repeated earthquakes. This study contributes to the evaluation on the value of behaviour factor, q based on design and structural performance. Beside, this study also checked the suitability of Modified Takeda Degrading Stiffness as hysteresis rule. As a conclusion, the value of behaviour factor, q is strongly influencing the seismic design. The total weight of steel reinforcement can be reduced up to 36.2% by using higher behaviour factor, q in design. From cyclic loading test, it can be concluded that the Modified Takeda Degrading Stiffness is suitable to be used as hysteresis rule in nonlinear time history analysis. The value of unloading stiffness, α is equal to 0.1 while the value of reloading stiffness, β is equal to 0.4. Based on evaluation on structural performance, the magnitude of maximum interstorey drift ratio caused by repeated earthquake reached up to 30.1% to 40.6% higher than the single earthquake. Therefore, the behaviour factor, q from 2.3 to 5.5 is acceptable to be used for seismic design of new reinforced concrete moment resisting frame building on Soil Type B in medium seismic region in Malaysia. On Soil Type D, the behaviour factor, q is limited from 2.3 to 4.54.